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The Arecibo Dual-Beam Survey: Filling the Gaps in the Extragalactic Census

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Abstract.

We present the Arecibo Dual-Beam Survey (ADBS), a "blind" 21cm survey for galaxies. The ADBS is the largest to date with the Arecibo radio telescope. We were able to achieve an rms sensitivity of 3-4 mJy in only 7 seconds. The ADBS covers substantially more volume than the Spitzak & Schneider (1998) and the Zwaan et al. (1997) surveys. It is surpassed by the Parkes HIPASS survey (Kilborn et al. 1999) but has much better angular resolution and sensitivity. We will discuss the HI sample and our efforts to quantify the completeness and reliability.

This is the first survey to use synthetic sources to establish the relation between the flux, line width, and completeness of the survey. An empirical understanding of these quantities is vital to the determination of the mass function. Even if we do not understand all of the reasons why we do not detect galaxies, the empirical understanding allows us to account for them properly.

In addition to the more general discussion of the ADBS survey, we will discuss galaxies which have large ratios of HI mass to optical area and probably have extended HI disks. We detect a much higher percentage of these high HI mass to optical area galaxies than are seen in optical surveys indicating that optical surveys miss these galaxies. Among these galaxies are also 7 galaxies with HI masses $< 10^8$ $M_\odot$. Based on the mass function of Schneider & Rosenberg (this volume), the low mass galaxies are an important part of the general galaxy population.

1. Introduction

We present the Arecibo Dual-Beam Survey (ADBS) and describe the original driftscan detection survey, the VLA and Arecibo follow-up observations, and the use of synthetic sources as a way of evaluating sample completeness. We then discuss the indications from the ADBS sample that even low surface brightness optical surveys have overlooked a population of compact and low surface brightness (LSB) galaxies that are found in HI surveys. The ADBS, and other "blind" HI surveys provide an important view of galaxy populations that is completely unbiased by star formation. Comparing our HI-selected sample to the dwarf and LSB sample of Schneider et al (1990, 1992), we find that the dwarf and LSB sample misses a significant fraction of the LSB population. The detection and study of this galaxy population is important for our understanding of galaxy formation and evolution.

2. The Arecibo Dual-Beam Survey

The goals of our survey are (1) to determine whether there are classes of galaxies that have been overlooked previously and (2) to help tie down the HI mass function with the larger number of sources in this sample. To achieve these goals a "blind" HI survey needs to detect galaxies down to the lowest possible HI fluxes. At least equally important is a detailed understanding of the survey limitations. The statistics of previous surveys have been insufficient to definitively establish the shape of the HI mass function at both the high and the low mass ends.

Zwaan et al. (1997) and Spitzak & Schneider (1998) undertook "blind" HI surveys, similar to the one discussed here, but neither had enough low mass sources to make a strong claim about the shape of the mass function. Schneider, Spitzak, & Rosenberg (1998) combined the two data sets and found evidence for a rise in the number of low mass sources, but the results are not definitive. The HIPASS survey, with its coverage of the entire Southern sky, should also contribute to our understanding of the HI mass function. The most recently published mass function contains 263 galaxies, comparable to the number in this survey (Kilborn et al. 1999) but only has 2 galaxies with $M_{HI} < 10^8$ M$\odot$ (converting to $H_0 = 75$ km s^{-1} Mpc^{-1}). HIPASS will cover significantly more volume than the ADBS in the end, but there are still issues that will make the detection of low mass sources more difficult (1) the rms = 13 mJy which means that low mass sources are only detected very nearby where determining the distance is difficult due to the effects of peculiar velocities (2) the telescope beam is so large that source confusion is a problem. For confused sources it has to be determined, after the fact, whether any of them could have been detected independently. We detect 7 sources with HI masses $< 10^8$ M$\odot$, almost as many as all of the previous "blind" HI surveys combined.

The Arecibo Dual-Beam Survey (ADBS) consisted of approximately 500 hours of driftscan observations at the Arecibo 305 m telescope before the Gregorian upgrade, between December 1993 and February 1994. These data consist of ∼300,000 spectra taken every 7 seconds and cover nearly 24 hours of time in each of 30 declination strips. The total sky coverage is approximately 430 deg^2 in the 3.3′ main beam. In these data we find 265 galaxies that were confirmed on follow-up.

Observing in driftscan mode meant that two feeds could be used simultaneously. We used the 21 cm and 22 cm circular polarization feeds, which have now been replaced by the Gregorian reflector. These were located on opposite corners of the carriage house and pointed 1.6° apart on the sky. Our ability to use two feeds doubled the area surveyed. The velocity coverage for the survey was –654 to 7977 km s^{-1}. This coverage was achieved over 512 channels in each of two polarizations for each of two feeds, totalling 2048 channels. The channel spacing was 16.9 km s^{-1} and the resolution was 33.8 km s^{-1} after Hanning smoothing. The average rms noise for the survey was 3.5 mJy.

One of the major challenges of any single-dish HI survey is to distinguish between real sources and radio interference. We used three tactics to address

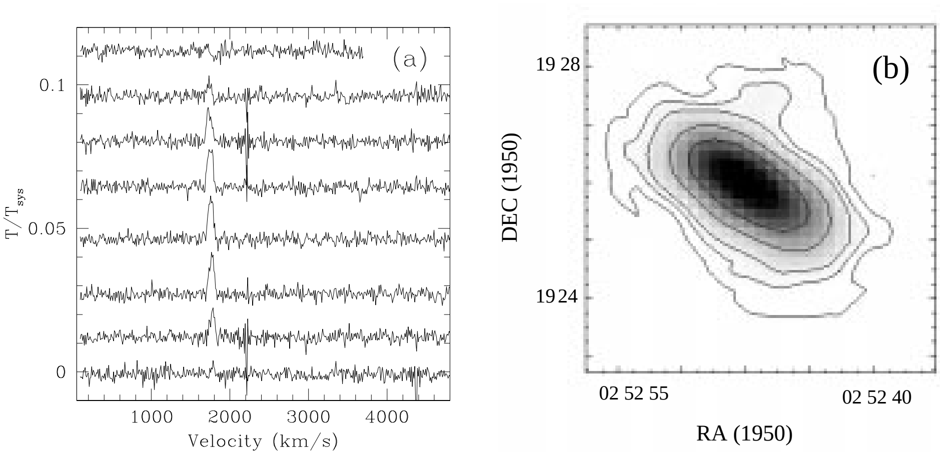

Figure 1. (a) An Arecibo "DECscan" observation. For the Arecibo follow-ups of the ADBS detections the telescope was fixed at the detection RA and driven in declination with spectra dumped every 10 seconds. (b) An example of a VLA D-array follow-up of the ADBS detections.

this problem while also increasing the volume coverage and improving the signal-to-noise: (1) Comparing data from the 21 and 22 cm feeds taken simultaneously – the interference usually enters through far sidelobes and appears in both feeds while real sources appear in only one. (2) Comparing left and right circular polarizations in each feed – the average of the two polarizations provides improved signal-to-noise while the difference is an additional check for interference since it is often highly polarized. (3) Observing each declination strip twice, on separate days, providing confirmation of the source detections.

While the driftscan technique allowed us to cover a large volume of space rapidly, it also gave us uncertainties of up to $\sim 7'$ in the declination position because the sources could be in the main beam or first sidelobe (or rarely farther out if the source was very bright at 21 cm). The lack of declination information meant that the sources needed to be reobserved to determine their positions and fluxes. We subsequently followed-up all of the candidate sources at the VLA and at Arecibo.

The VLA follow-up consisted of 10 minute snapshots in D-array made in January 1998 for 99 sources (90 were detected) most with velocities less than 3000 km s^{-1}. The rest of the galaxies in the detection survey were followed up at Arecibo. To improve the coordinates and fluxes from those determined in the detection survey we observed in "DECscan" mode. We chose to track the telescope at the detection right ascension and drive the telescope $\pm 7.5'$ from the driftscan declination. The telescope was driven in declination for a total of 3 minutes and spectra were dumped every 10 seconds providing 18 spectra separated by $50''$. The resulting RMS sensitivity is 1.5 mJy. Figure 1 shows an example of a follow-up VLA map and a "DECscan" observation.

A complete discussion of the detection and follow-up surveys is presented by Rosenberg & Schneider (2000).

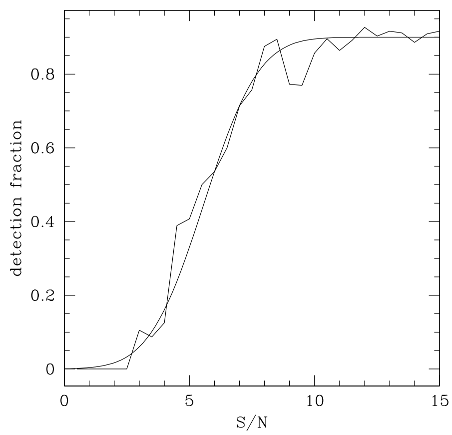

Figure 2. The relationship between % completeness and S/N determined from the synthetic sources that were inserted into the data before the data processing. The dashed line is a smoothed version of the data and the solid line is a fit. Note that the completeness never reaches 100% and falls off precipitously below 8σ.

3. Synthetic Sources

We have made use of synthetic sources as a means of analyzing our sample completeness which is vital for determining the mass function of galaxies. The sources that were used covered a wide range of luminosities and line widths and were given realistic line profiles. The sources were then inserted into the data prior to the reduction procedure to be detected along with the real sources. Figure 2 shows the resulting completeness statistics for these sources. The sample is not complete even at high signal-to-noise levels because sources at the edges of the bandpass were sometimes fit as part of the continuum level. Also, the completeness does not have a sharp edge, but falls off fairly rapidly for sources at $< 8\sigma$. The shape of this curve is very important for the determination of the mass function (Schneider & Rosenberg, this volume).

4. HI-Dominant Galaxies

We define HI-dominant galaxies as those with ratios of $M_I/M_{HI} < 1$. Spitzak & Schneider (1998) studied the properties of these galaxies in their HI-selected sample and found that they tend to be similar to, although more extreme than, optically-selected LSBs. As HI-dominance increases, surface brightness tends to diminish and the galaxies' colors tend to be bluer. Given the apparently extreme nature (relative to optical samples) of the HI-selected Spitzak & Schneider (1998) sample, we would like to use the larger ADBS survey to address the question: Do HI surveys detect a population of galaxies that is different from what is found in optical surveys?

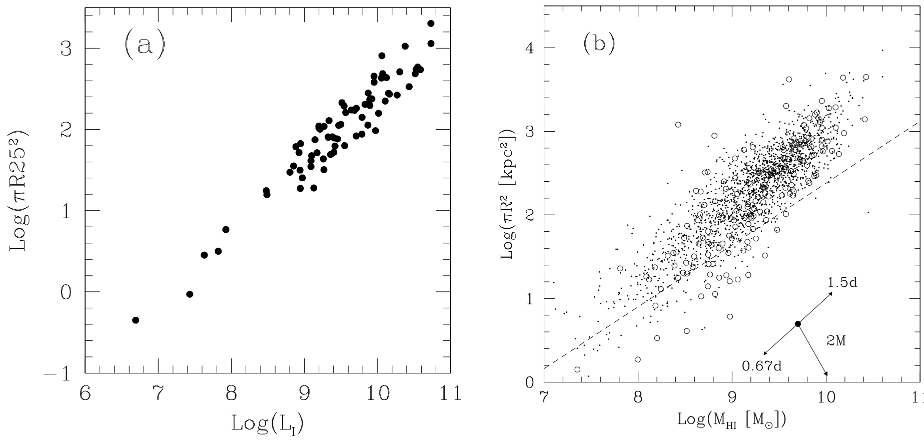

Figure 3. (a) The relationship between I-band luminosity and optical area determined from the Spitzak & Schneider sample. (b) The relationship between HI mass and optical area. The dots are LSB and dwarf galaxies, the open circles are the ADBS sources. The dashed line shows $L_I/M_{HI} = 1$ assuming a linear fit to Figure 4a. The errorbars show the effect of systematic errors in distance and mass on the data.

Since we do not currently have optical photometry for these galaxies, we need to find a surrogate for I-band luminosity. What we have for the ADBS galaxies is size measured on the Digitized Sky Survey (DSS) images. Figure 3a shows that there is a tight correlation between $\log(L_I)$ and log(area) for the galaxies in the Spitzak & Schneider sample. Figure 3b shows the relationship between optical area and HI mass for optically selected LSB and dwarf galaxies from Schneider et al. (1992, 1990; filled dots) and ADBS galaxies (open circles). The dashed line in Figure 3b is approximately $L_I/M_{HI} = 1$ as derived from the Spitzak & Schneider relationship. If the LSB and dwarf galaxy sample and the ADBS select the same populations of HI-dominant galaxies, then there should be no statistically significant difference in the percentage of galaxies below and above the $L_I/M_{HI} = 1$ at a given mass. What we find instead is that $\sim$27% of the galaxies in the ADBS sample are below the line in the mass range between $\log(M_{HI}) = 8.8$ and $\log(M_{HI}) = 9.2$ while only $\sim$5% of the LSB and dwarf sources are below the line. Since we know that the ADBS is nearly complete in the 10^9 $M_\odot$ range, the lack is due to an optical bias that results in incompleteness even in this LSB and dwarf sample. We expect this incompleteness to increase at lower HI masses (Schneider & Schombert 2000).

Figure 4 shows some examples of the HI-dominant galaxies that we find in the ADBS. The top panels are the VLA D-array maps for these galaxies while the lower panels are the corresponding DSS images. For these galaxies there is little or no optical emission obviously associated with the HI source. In the end, there appear to be very few, if any HI sources with no optical counterparts in deep optical images, but many of the "possible" optical counterparts are extremely small and faint. One of the main reasons for the incompleteness even of LSB samples is the minimum angular size requirement. Even if it is possible

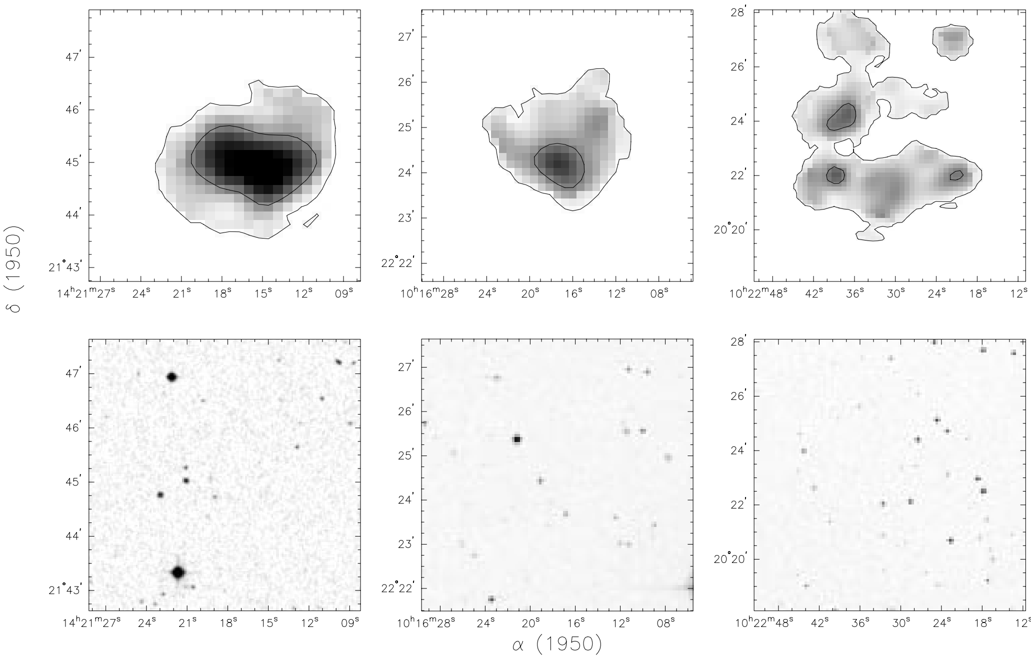

Figure 4. VLA D-array maps (top row) and the corresponding DSS images (bottom row) for 3 HI-dominant galaxies in the ADBS survey.

to detect these HI sources optically they are very difficult to detect and there is substantial incompleteness in the selected population.

It is important to detect and study the HI-dominant galaxy population in a complete and unbiased way because of the significance of these galaxies for understanding galaxy populations and evolution. Galaxy evolution is about the conversion of reservoirs of HI gas to stars. Figure 5 shows the relationship between the gas-to-total-mass and stars-to-total-mass ratios. This figure shows that there is a fairly consistent ratio of baryonic mass to total mass. The most extreme galaxies on either end of this plot are missing because the most HI-dominant galaxies are not measured optically while the most stellar-dominated galaxies do not have detectable HI. In order to have a complete understanding of the evolutionary relationship between gas and stars we must probe both ends of this distribution. The best way to probe the HI-dominant end in an unbiased manner is to use HI-selected samples.

5. Conclusions

We have completed a survey of $\sim$ 430 deg^2 at 21 cm and have detected 265 galaxies, 7 of which are below 10^8 M$\odot$. In order to understand the significance of these low mass sources and to generally understand the statistics of our detection survey, we have used synthetic sources. These sources allow us to map out our completeness as a function of signal-to-noise.

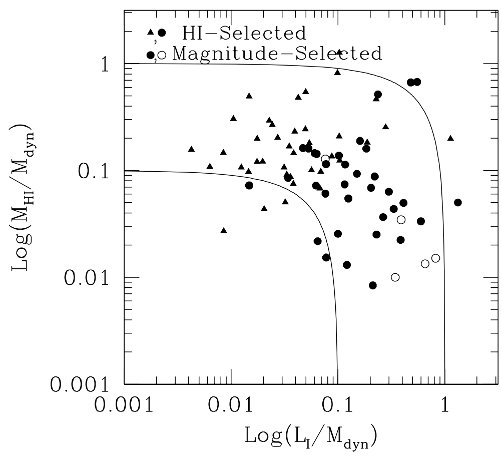

Figure 5. The relation between stellar mass, HI mass, and total mass in galaxies. The solid lines show $M_{HI}+M_I$ equals 0.1 M_{tot} and 1.0 M_{tot}.

We have also compared the detection of HI-dominant galaxies in the ADBS to their detection in the Schenider et al. (1992, 1990) dwarf and LSB sample. We find that when we select galaxies by their HI, a method that is completely unbiased by the galaxy's surface brightness, we find a much larger fraction of the galaxy population to be HI-dominant than is found by the LSB and dwarf galaxy sample. In addition, the ADBS galaxies are more extreme in their HI-dominance, surface brightness, and color characteristics than those detected in the LSB and dwarf galaxy sample. The LSB and dwarf galaxy survey, and probably other optical LSB surveys, is not finding all of the galaxies and it is not detecting them in a manner which is unbiased by their surface brightness properties. In order to understand the processes of galaxy formation and evolution we must understand the range of star forming environments for galaxies including the HI-dominant galaxies found in "blind" HI surveys.

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